HUMPBACK WHALE HABITAT USE PATTERNS AND INTERACTIONS WITH VESSELS AT POINT ADOLPHUS, SOUTHEASTERN ALASKA

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By

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Abstract

Humpback whales at Point Adolphus, in southeastern Alaska, are faced with the challenge of maximizing their energy gain from feeding and minimizing energy losses that can occur due to disturbance by vessel traffic. Point Adolphus is unique because of abundant prey resources that attract high concentrations of humpback whales during the summer and high levels of vessel activity. Using scan sampling and focal behavior observation sessions data were collected from an elevated shore station on the northern coast of Chichagof Island in 2001. Humpback whale numbers peaked during early ebb tide. Whales were distributed west during ebbing tides and east during flooding tides. During flood tides, humpback whales exhibited non-directional movement. Differences in humpback whale numbers, distribution and movement patterns in relation to tide appeared related to small-scale fronts and headland wake effects associated with Point Adolphus. Overall, humpback whale swimming speeds were faster when the number of vessels present was greater and distance to the nearest vessel was smaller. However, responses of individual whales differed. Humpback whales at Point Adolphus appear to have developed strategies to exploit predictable times to feed which are tidally-induced and practice short-term avoidance strategies that may reduce the effects of vessel traffic.

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Introduction

Humpback whales (*Megaptera novaeangliae*) occur primarily in shallow coastal waters and are affected by near shore oceanography and human activities such as coastal development and commercial and private vessel traffic (Norris and Reeves 1978). Humpback whales are migratory baleen whales, mating and calving in subtropical waters during the winter and feeding in high-latitude waters. Subtropical waters are relatively unproductive; therefore, humpback whales obtain the bulk of their entire caloric intake for the year while in high-latitude waters (Dawbin 1966, Krieger and Wing 1984). There is concern that increasing vessel activity in high-latitude coastal areas may disturb humpback whales at preferred feeding locations (Norris and Reeves 1978, Baker and Herman 1989). Potential problems include the effects of pollutants, incidental take by fishing gear, collisions with ships and disturbance from underwater sound (Richardson et al. 1995). This study investigates movement patterns of humpback whales due to oceanography and vessels at a high-latitude feeding area.

Humpback whale distribution and abundance is strongly correlated with the abundance of their prey, euphausiids and small schooling fishes, within seasons and among years (Wing and Krieger 1983, Piatt et al. 1989). Due to humpback whales' size and caloric requirements, areas with prey patches of adequate size to sustain their feeding over days or weeks may be found only in a few areas (Piatt and Methven 1992). In selecting foraging locations and feeding times, density of prey patches and density of prey within patches is as important as consistent prey abundance. For example, in Fredrick Sound, Alaska, densities of at least 10,000 euphausiids m^{-3} were necessary to meet humpback whale caloric requirements in 4.5 hours of feeding per day (Dolphin 1987c).

Foraging strategies in high-latitude habitats differ according to prey type and influence humpback whale social organizations (Perry et al. 1990, Sharpe 2001). Associations among humpback whales feeding on euphausiids tend to be fluid, while humpback whales feeding on small schooling fish tend to form more stable or repeated associations.

Stable and behaviorally coordinated groupings of humpback whales, not associating by kinship or sex (Gabriele et al. 1995), have been observed in southeastern Alaska (Sharpe 2001). Apparently, groups of humpback whales with long-term associations and closely coordinated behaviors are more efficient in herding agile, fast-swimming fishes than those feeding alone (singletons) or in pairs (Perry et al. 1990, Sharpe 2001).

Knowledge about hearing thresholds of humpback whales is limited. There have not been any direct measurements of humpback whale hearing, however anatomical and evolutionary evidence and their vocalization range suggest that baleen whales are adapted to hear low frequencies. Anatomy and biomechanical properties of the basilar membrane indicate sensitivity to frequencies from 700 Hz – 10 kHz (Houser et al. 2001). Based on the assumption that evolutionary selection should favor individuals whose sounds optimize the transmission properties of the environment, shallow water transmission loss and ambient noise suggest selection should favor sounds at 100 – 500 Hz (Clark and Ellison 2002). Most baleen whale vocalizations occur at less than 1 kHz and most well-studied baleen whale species' sounds include components less than 50 Hz (Richardson et al. 1995), including humpback whales at Point Adolphus, Alaska. Humpback whale calls made during feeding, i.e., assembly and prey manipulation calls, range from 20 Hz – 2 kHz (Richardson et al. 1995, Sharpe 2001, Cerchio and Dalheim 2001). Based on behavioral response during playback of a conspecific feeding call and a synthetic sound, humpback whales can hear received broadband levels as low as 102 dB re 1 μPa and 106 dB re 1 μPa respectively (Frankel et al. 1995b).

Humpback whales rely on vocalizations and other sound generation (e.g., flipper and fluke slapping, breaching) for communication with each other and herding of prey (Sharpe 2001) and apparently sensing their environment through echo-ranging (Clark and Ellison 2002). Man-made underwater sound, such as vessel noise, can affect whales in three ways: blocking basic communication and environmental cues, affecting behavior by interrupting activities and/or displacing whales, and temporarily or permanently reducing hearing sensitivity (Richardson et al. 1995). Thus, the potential impact of vessel sound is a concern in high-latitude foraging areas.

Vessel sound levels and frequencies depend on ship size and speed (Richardson et al. 1995). Vessels with high rpm engines such as outboards create primarily high frequency sounds (Richardson et al. 1995). Larger vessels and vessels traveling at faster speeds tend to produce higher sound levels (Kipple and Gabriele 2004). Large vessels such as cruise ships have high sound levels at low frequencies (Richardson et al. 1995). Cruise ships traveling 10 knots range in volume from 150-164 dB re 1 μPa at 500 Hz at a distance of one yard (Kipple 2002). The primary sources of sounds from all vessel classes are propeller cavitation, propeller singing and propulsion engines or other machinery such as rotating shafts, gear reduction transmissions, pumps and generators. There is also considerable variation in these parameters among vessels of the same size. For example, propeller cavitation from cruise ships traveling at 10 knots can vary by 16 db re 1 μPa (Kipple 2002). Vessel construction materials and hull design also influence vessel sound output.

Humpback whale reactions to vessels are presumably reactions to noise (Richardson et al. 1995). Reactions can occur at long distances from the vessel (Baker and Herman 1989) and follow changes in engine and propeller speed (Richardson et al. 1995). For example, baleen whales near Cape Cod were found to ignore most weak vessel sounds, but moved away in response to strong or rapidly changing vessel noise (Watkins 1986). In Baja California, gray whales abandoned a calving lagoon for several years and returned after vessel traffic had diminished (Bryant 1984). Low-frequency sounds emitted by large vessels overlap humpback whale vocalization and presumed hearing ranges (Richardson et al. 1995). The potential impact of various sound intensities and frequencies, i.e., masking of calls, disturbance or injury, is unknown (Erbe 2003).

Humpback whales feeding in northern southeastern Alaska (Figure 1) during the summer are part of the central North Pacific stock that migrate after mating and calving in Hawaii each year (Perry et al. 1990). In U.S. waters, they are protected under the Endangered Species Act of 1973. The population estimate for the central North Pacific stock was 4,005 humpback whales (CV = 0.095) in 1993 (Calambokidis et al. 1997) and is thought to be increasing 7% per year (Mobley et al. 2001). Approximately 1,000 (961, 95% CI: 657 – 1076) humpback whales feed in northern southeastern Alaska annually (Straley et al. 2002). Humpback whales in southeastern Alaska show a high level of fidelity to feeding areas. Site fidelity analyses of data collected in Glacier Bay, Sitka Sound and Fredrick Sound from 1994 through 2000 estimated that 74 – 81% of humpback whales return to the same feeding area in subsequent years (Straley et al. 2002).

Observations of the seasonal aggregation of humpback whales in the waters of Glacier Bay and Icy Strait, by a local science teacher and his high-school students, began in 1974 (Jurasz and Palmer 1981). In the early 1980s, researchers from the University of Hawaii conducted a comprehensive study of vessel effects on humpback whales in Glacier Bay, Icy Strait and Fredrick Sound (Baker et al. 1983). Since 1985, Glacier Bay National Park biologists have monitored humpback whale population characteristics using photographic identification. Park biologists photograph each whale's flukes and dorsal fin and compare the black and white pigment pattern on the ventral side of the flukes and the shape of the dorsal fin to previously cataloged photographs to determine the identity of each whale (Neilson and Gabriele 2005). The Glacier Bay database includes humpback whales sighted for their entire life-spans and humpback whale sighting histories spanning 30 years (Gabriele pers. comm.).

Study Area

As the humpback whale population recovers from commercial whaling, and the marine tourism industry develops in southeastern Alaska, the volume of transient, local, and commercial traffic and sport fishing activity in Icy Strait continues to increase (National Marine Fisheries (NMFS) 2001a). Persistent prey resources at Point Adolphus attract humpback whales, and consequently whale-watching vessels, which along with fishing vessels, contribute to high levels of vessel activity. Point Adolphus is a destination for boat-based tourist activities and it is also a major and growing destination for kayak-based camping and wildlife viewing. Point Adolphus is also a stopping point for tourist vessels enroute to Glacier Bay. Local traffic includes travel between small communities in Icy Strait, travel to recreation and subsistence sites, and use of the area itself for subsistence fishing, hunting, camping and beachcombing. Icy Strait is a major route for shipping between inside waters and the outer coast and for vessels transiting to commercial fishing grounds along the outer coast of southeastern Alaska. Point Adolphus is a headland projecting into Icy Strait, and transiting closely to Point Adolphus is the shortest route for vessels traveling either westbound or eastbound which also contributes to the volume of vessel activity in the near shore area.

The Point Adolphus region, the northernmost extension of Chichagof Island in Icy Strait directly opposite Glacier Bay (Figure 1), is unique due to continually abundant prey resources that attract high concentrations of humpback whales during the summer. It also has high levels of vessel activity for the reasons described above. Biomass surveys conducted in Glacier Bay and Icy Strait found that high-density patches of either small-schooling fishes or euphausiids were concentrated in relatively few areas in shallow, near shore waters (Wing and Krieger 1983, Robards et al. 2003). The prey density near Point Adolphus ranks among the highest surveyed, containing prey patches greater than 0.1 fish m^{-3}, which is suitable for humpback whale foraging (Krieger and Wing 1984, Dolphin 1987c, Robards et al. 2003). Forage species at Point Adolphus include Pacific herring (*Clupea pallasii*), juvenile walleye pollock (*Theragra chalcogramma*), Pacific sand lance *(Ammodytes hexapterus)*, capelin (*Mallotus villosus*), euphausiids (*Thysanoessa raschii*) and amphipods (*Cyphocaris challengeri*) (Wing and Krieger 1983, Robards et al. 2003).

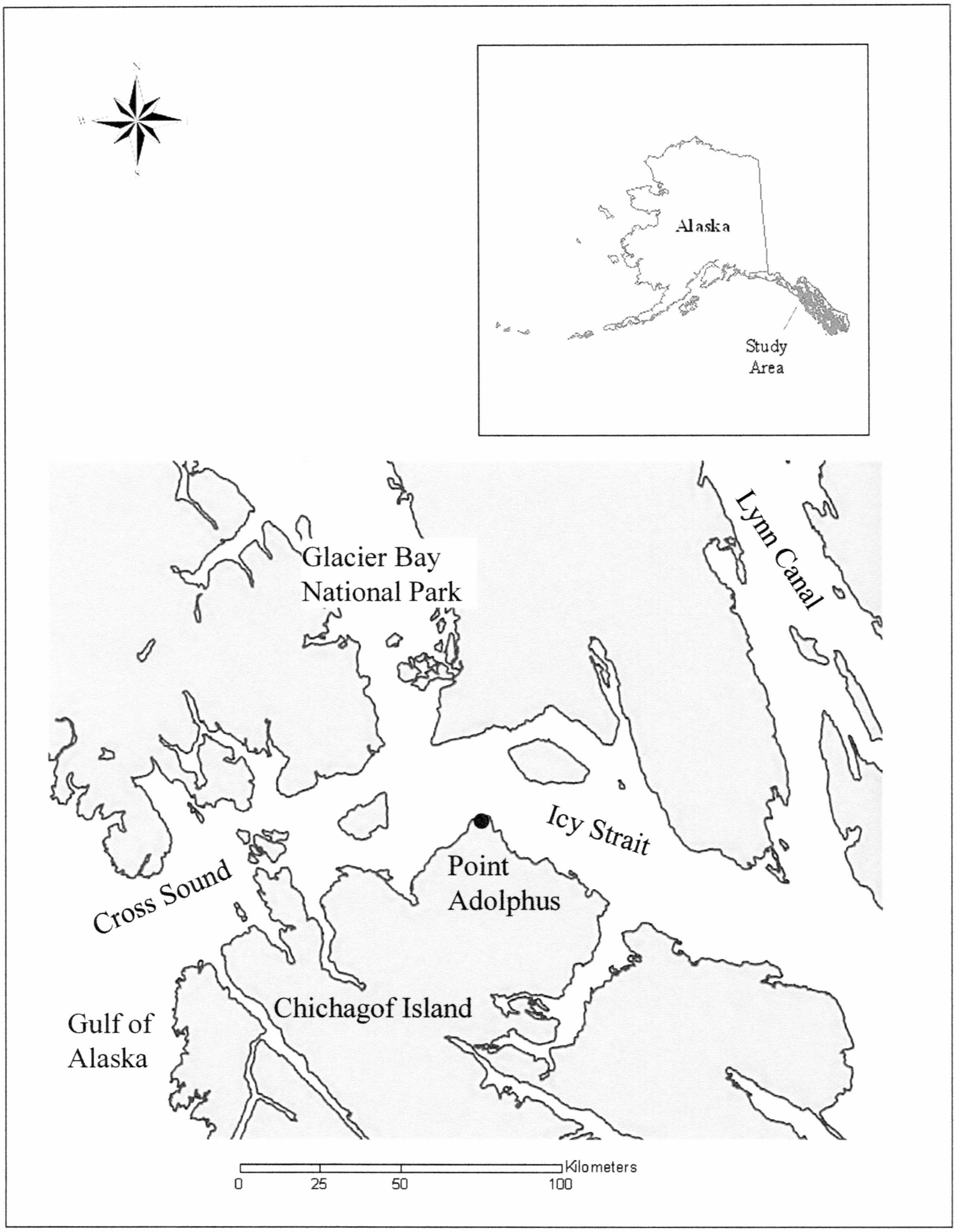

Figure 1. Map of Icy Strait and Point Adolphus in northern southeastern Alaska.

Oceanographic factors at Point Adolphus, such as proximity to fjord processes of Glacier Bay and small-scale fronts and headland effects, sustain and concentrate these prey resources. Icy Strait is the main route of tidal exchange for water moving from northern southeastern Alaska to the Gulf of Alaska at Cape Spencer. Tidal exchange on a mixed semidiurnal tidal schedule can create current speeds of greater than 1.6 knots (Nautical Software 1997). These strong currents interact with intricate bathymetry in the vicinity of the Point Adolphus headland to create complex salinity, density and temperature, and flow patterns that concentrate prey, making this an important foraging area for marine mammals, including humpback whales (Krieger and Wing 1984, Robards et al. 2003). Nearby Glacier Bay has high nutrient availability (Hooge and Hooge 2002, Etherington et al. 2004) and is a nursery area for forage fish (Robards et al. 2003). Resources from Glacier Bay are transported and concentrated along tidal fronts in Icy Strait (Hooge and Hooge 2002, Etheringon et al. 2004).

The waters near Point Adolphus are complex acoustically. Sound transmission is affected by the acoustic properties of the bottom and the surface and water column discontinuity created by differing water masses moving back and forth with each tidal exchange (Watkins and Goebel 1984); so sound transmission is variable and site specific (Richardson et al. 1995). The portion of Icy Strait in the study area is shallow near shore, approximately 3 – 4 m, dropping off sharply to 40 – 55 m at approximately 250 m from shore and down to 100 m at approximately 500 – 1500 m from shore (Figure 2). Due to the bathymetry at Point Adolphus, the water is sufficiently deep near shore that large vessels such as cruise ships commonly pass within approximately 1 km of shore. Underwater sound levels in the near shore area at Point Adolphus, produced by vessel traffic, have not been quantified but are likely to be high (NMFS 2001a).

Point Adolphus's oceanographic processes produce rich coastal habitat for humpback whales. Point Adolphus is an area in which humpback whale habitat and intense human activity overlap, creating an opportunity to investigate humpback whale habitat use patterns and possible impacts from vessel activity. This study will (1) document distribution and abundance of humpback whales in relation to the tide and (2) investigate changes in behavior in relation to presence and proximity of vessels.

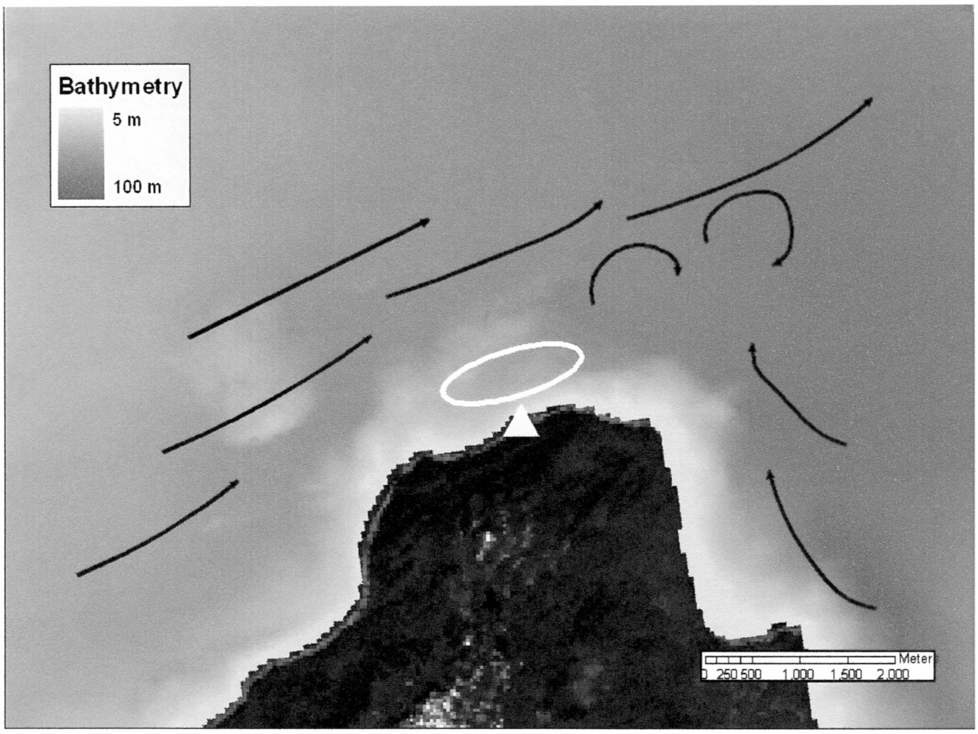

Figure 2. Map of the Point Adolphus, Alaska headland and near shore area. Blue shading represents water depth (Albert 2002). Triangle represents shore station location. Ellipse represents approximate acoustic sampling location. Arrows represent presumed current flow during flood tides (Based on Alldredge and Hamner 1980).

Methods

Field Data Collection

Humpback whale and vessel observations were made between June 7 and September 11, 2001 from an elevated observation site (termed a 'shore station') at Point Adolphus (Figure 2) on the north coast of Chichagof Island (58° 17.22 N, 135° 48.20 W). The shore station was on a bluff 16.6 m above sea level. The visible area of ocean from this vantage point had approximately a 14 km radius. Observation sessions were conducted by a crew of three people acting as behavioral observer, theodolite operator, and computer operator.

All humpback whale and vessel locations were recorded with a Sokkia DT500 theodolite with 5-sec precision and 30-power magnification. The theodolite was linked to a MacIntosh Powerbook 1400/166c laptop computer running a time-synchronized data-collection program, Aardvark, developed for shore-based whale studies (Mills 1996). Humpback whale and vessel locations (referred to as 'fixes') were calculated using horizontal and vertical angles measured with the theodolite. Subsequent analysis using "Aardvark" converted theodolite angles to Cartesian coordinates and latitude/longitude, with correction for curvature of the earth, tide height and theodolite height. Scan sampling and focal behavior observation sessions were used to collect humpback whale and vessel data (Altmann 1973). In association with humpback whale observations, we also observed cruise ship activity to determine the frequency of cruise ship course deviations and changes in speed for whale-watching at Point Adolphus (Appendix A).

Scan Sampling

Scan sampling (Altmann 1973) was used to record humpback whale distribution and abundance. During each 15-min scan, the location of each humpback whale pod and vessel in the observation area was documented at least once. At the beginning of a scan, the theodolite operator recorded the location of all vessels in the area using the theodolite. Vessels were classed as non-motorized vessels, motorized vessels with single or double outboard motors, vessels less than 200 feet in length with inboard motors and vessels greater than 200 feet in length with inboard motors. Vessel activity, e.g. moving or stationary, was recorded. For the purposes of this study, a humpback whale pod was defined as one or more whales within five whale-lengths of each other, moving in the same direction and/or surfacing and diving in synchrony with each other. The position of each humpback whale pod was fixed once during the 15-min scan. If at the end of the timed scan, there were remaining humpback whales and vessels that had been observed but their location was not yet recorded using the theodolite, an additional 5-min observation period was used to fix their location. Several scans occurred during each sampling day with the goal of obtaining at least one scan during morning (0700-1100), midday (1100-1500) and evening (1500-1900), interspersed with focal observations.

Focal Pod Behavior Observation Sessions

Humpback whale behavior was investigated using focal pod behavior observation sessions (Altmann 1973). Focal pod observation sessions were the observations and description of the precise location and behavior of one humpback whale pod and the location and movement of all vessels visible from the shore station. Pods selected for observation sessions met two criteria; the pod was within approximately 4 km of the shore station and close enough to observe all respirations and behaviors during surfacings. Focal pod locations were recorded every surfacing or as close to every surfacing as possible. Focal sessions were terminated if humpback whales joined or left the pod or if a pod could no longer be reliably tracked. The locations of the nearest vessels were recorded continually if possible, primarily while the focal pod was submerged, and all vessels in the observation area were recorded at least once during each dive. Locations of pods, other than the focal pod, in the area were recorded as time permitted. Observers used their understanding of average humpback whale surface and dive behavior to track the focal pod, e.g., foraging humpback whale swim speeds (3.9 km/hr; Baker and Herman 1989), dive times (2.8 min, 1.2-8.2 min), surface durations (0.7 min, 0.4-2.8 min), and number of blows per surfacing (3.2 blows, 1.6-10.6 blows; Dolphin 1987b). Humpback whale behavior was described using an ethogram (list of codes to describe behavioral events) and the general behavioral state of the focal pod (Frankel et al. 1995a; Appendix B). Behaviors recorded were categorized as associated with respiration, submergence or surface activity.

Individual humpback whales were visually identified to confirm that focal observations stayed with the same focal pod (Mann 1999). The unique pattern on the underside of their flukes and shape of their dorsal fins were used to identify individual humpback whales (Jurasz and Palmer 1981, Katona and Whitehead 1981). Flukes and dorsal fins of focal whales were compared to cataloged photographs of humpback whale flukes and dorsal fins compiled by the Glacier Bay National Park humpback whale monitoring program (Gabriele et al. 1995, Straley and Gabriele 2000). If a focal whale was found in the catalog, the humpback whale's identification code from the monitoring program was used to identify that humpback whale, and if not it was given a new observation number. New, sequential observation numbers were assigned each day (i.e., the first humpback whale observed each day was assigned the number one). Though observers in this study did not obtain identification photographs of focal whales to verify their identity, they only attributed a focal session to a particular "known" humpback whale when the behavioral observer and the theodolite operator were 100% certain of its identity. The theodolite operator and behavioral observer gave each focal session a confidence rating based on the ability to observe respirations, behaviors or both (Frankel et al. 1995a; Appendix C). Ratings were updated when humpback whale distance or viewing conditions changed.

Acoustics

Underwater sound was recorded with the goal of representing a range of acoustic conditions experienced by humpback whales observed during focal behavior sessions. Recordings were made using a system composed of a hydrophone with a Shure-14 preamplifier and Sony DT-100 digital audio tape (DAT) recorder housed aboard a kayak. The hydrophone was suspended at a depth of 3 - 10 m over the side of the kayak that remained in approximately 35 - 45 m of water within approximately 300 m radius from the shore station. The kayak's location was fixed with the theodolite by shore observers to determine the position of the hydrophone relative to humpback whales and vessels during recording. Clocks on the DAT recorder and the shore computer were synchronized to link acoustic and visual data.

Analysis

Humpback Whale Distribution and Abundance in Relation to Tide

Data collected during scan sampling were used to investigate humpback whale distribution and abundance in relation to tide. Humpback whale distribution was plotted using ArcGIS (ESRI 2004) by combining a raster LANDSAT Enhanced Thematic Mapper image, bathymetry shapefile (Albert 2002), humpback whale coordinates, date, time, tide direction and phase. Tide directions were defined as flood or ebb. Tide phases were defined as spring, neap and normal. Spring tide was the phase occurring for three days at full and new moon when the extremes of tide highs and lows are the greatest. Neap tides occurred for three days at first and third quarter moon when high and low tides were at a minimum. Tides during remaining days were considered 'normal' tides. Definitions of tide directions used for humpback whale abundance analysis were on a finer scale: early flood, the first two hours after low tide; mid flood, the third and fourth hours after low tide; late flood, the fifth and sixth hour after low tide; early ebb, the first two hours after high tide; mid ebb, the third and fourth hours after high tide; and late ebb, the fifth and sixth hour after high tide.

Humpback whale pod distributions during differing tide directions and phases were compared using a multivariate analysis of variance (MANOVA; Zar 1999, SAS 2005). Each humpback whale pod location in latitude and longitude, as response variables, was compared to tide direction and phase. Wilks' determinant ratio test statistic was used as the MANOVA statistic (test statistic F). Directional distributions for each humpback whale distribution relative to tide were determined by calculating standard deviational ellipses. One standard deviation of the x coordinates and y coordinates from the mean center of each humpback whale distribution define the axes of the ellipse (ESRI 2004). Humpback whale abundance and tide direction and phase were compared using an analysis of variance (ANOVA, test statistic F) or a Kruskal-Wallis test. The Kruskal-Wallis test (test statistic H), a nonparametric alternative to an ANOVA performed on ranks rather than raw values (Zar 1999, SAS 2005), was used when assumptions of an ANOVA were not met.

Humpback Whale Behavior in Relation to Vessels

Data collected during focal behavior sessions were used to investigate behavioral change in relation to the number of vessels, the distance to nearest vessel and vessel type. Humpback whale swim speed was calculated for each 'leg' of its track which described the distance and time elapsed between two fixes. Swim speed was the primary behavior investigated with respect to vessel independent variables. Swim speed legs that were considered extreme values, (i.e., indicating humpback whale swim speeds greater than 20 km/hr), were deleted (Bauer 1986). Surface and underwater swim speed legs were both included in the analysis. Humpback whale behaviors at the surface and underwater, especially in foraging humpback whales, are presumably different, i.e., a decrease in swim speed may be related to an increase in dive depth, and this difference affects interpretation of these results. Additional behaviors used in the analysis included dive duration (the time between surfacings), blow interval (the duration in seconds of intervals between blows while at or near the surface) and surface blow rate (the number of blows observed during a surfacing divided by time at the surface between dives) (Baker and Herman 1989). Surface blow rates of pods with more than one humpback whale were calculated by counting all of the blows observed during a surfacing and dividing by the total by the number of humpback whales in the pod. Results related to surface blow rate are reported in the appendix only (Appendix D). Numbers of vessels present and distance to the nearest vessel were independent variables. Swim speed during each leg, blow interval, and dive duration were dependent variables compared using a Student's t test (test statistic t) or a Mann-Whitney U test. The Mann-Whitney U test (test statistic U), a nonparametric alternative to a t-test performed on ranks rather than raw values (Conover 1999, Zar 1999, SAS 2005), was used when assumptions of a t-test were not met. Vessel types were independent class variables, numbers of vessels were continuous independent variables and swim speed legs were continuous dependent variables compared using an analysis of covariance (ANCOVA, test statistic F; Sokal and Rohlf 1995, SAS 2005).

Acoustics

Underwater recordings were selected as representative samples of the acoustic environment at Point Adolphus, i.e., ambient noise, humpback whale vocalizations, frequently observed vessels, vessel types, and combinations of vessels or changing engine noise. Representative samples were identified by listening to the recordings and comparing the sounds to sightings from the shore station during recording. Samples were saved as .wav files. Spectrograms were created of sounds to illustrate ambient noise, humpback whale vocalizations and various compositions of vessels using Raven interactive sound analysis software (Charif et al. 2004) and were used qualitatively.

Results

Data

We collected data on 56 days, comprised of 103 15-min scans and 139 focal sessions. Focal sessions averaged 52 min each and ranged from 2 min to 241 min (122 hours total). Fifty-four scans occurred during flood tide and 50 scans occurred during ebb tide. In contrast, 101 focal sessions began during flood tide and 38 focal sessions began during ebb tide.

Scan Sampling

Humpback whales were present during 100 of 103 scans. Vessels were present during 102 of 103 scans. Only during one scan were there no vessels and no whales present. The average number of humpback whales observed did not differ by time of day (Figure 3). An average of 5-6 humpback whales was observed during morning, midday and evening scans. This average is 5-6% of the total number of humpback whales observed by Glacier Bay National Park biologists in the waters of Glacier Bay and Icy Strait between June 1 and August 31, 2001 (99 humpback whales) (Neilson and Gabriele 2005). The average number of vessels observed differed by time of day and was greatest during midday scans (Figure 3). Types of vessels observed differed overall and by time of day (Appendix E).

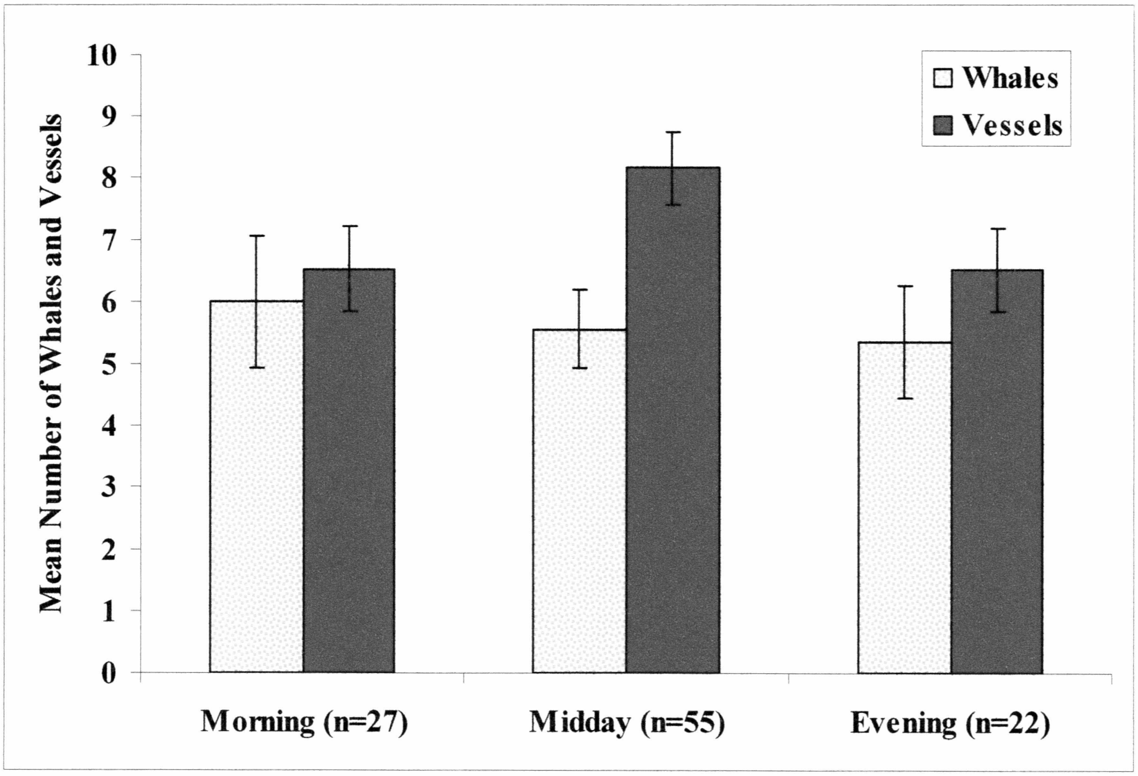

Figure 3. Humpback whales and vessels observed during scans. Means and standard errors of the number of humpback whales and vessels per scan during the morning (0700-1100), midday (1100-1500), and evening scans (1500-1900) at Point Adolphus. Error bars are 95% confidence intervals.

Focal Pod Observation Sessions

During an average focal session, humpback whales had three vessels within approximately 14 km traveling at an average of 9.3 $\pm$ 0.2 km/hr. The distance to the nearest vessel was 1656 $\pm$ 52 m on average. There was at least one vessel within 100 m of the focal pod during 30 of the 139 focal sessions. Vessels within 100 m traveled between 0.04 to 50 km/hr, 5.7 $\pm$ 1.2 km/hr on average. There were few focal sessions without vessels present. Only during 10 of 139 focal sessions were there no vessels present for 15 min or longer. The maximum time without any vessels present during a focal session was 75 minutes.

<u>Acoustics</u>

Ten hours of sound were recorded between August 27 and September 11, 2001 in a range of weather conditions and numbers and compositions of humpback whales (i.e., singletons, mother and calf pods) and vessels. Due to uncertainties in instrument calibration during recording, which were not discovered until analysis, we were not able to determine absolute sound levels. Therefore acoustic data were useful for creating spectrograms, but not for analysis. Spectrograms were created of ambient sounds levels, whale vocalizations (Figure 4) and vessel sounds (Appendix F).

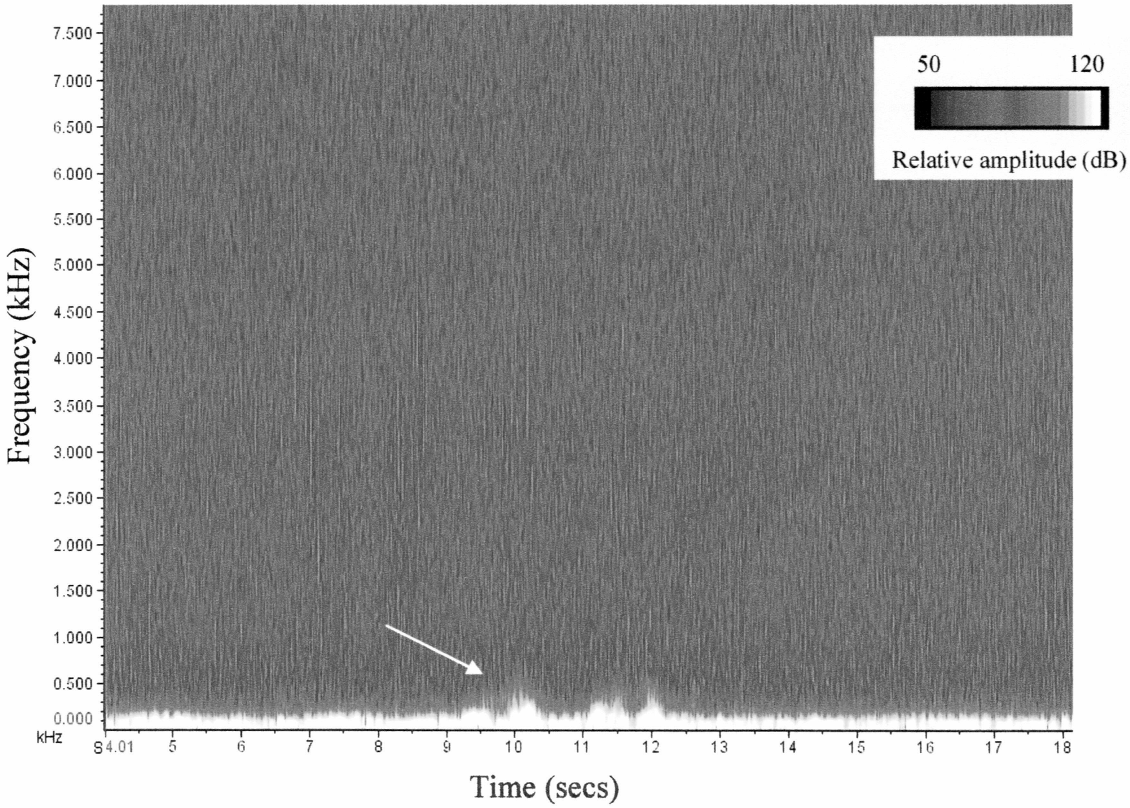

Figure 4. Spectrogram of underwater sound with whale vocalization. Sound was recorded on 29 August 2001 at 1529 during late ebb tide at Point Adolphus. Arrow shows vocalization sound energy concentrated at 0-500 Hz. There were two inboards <200' present, one stopped at approximately 2 km and the other at approximately 10-12 km from the hydrophone. An outboard was observed 2 min after this recording at approximately 8 km from the hydrophone.

Relative Humpback Whale Distribution and Abundance in Relation to Tide

Relative humpback whale pod locations differed in relation to tide direction and phase. Humpback whales were distributed more to the east during flooding tides than during ebbing tides (F=16.94, n=32 flood, n=29 ebb, p<0.0001) on normal tide phases (Figure 5). Humpback whale distribution did not differ in the north-south (offshore-onshore) direction during normal tide phases (F=0.68, n=32 flood, n=29 ebb, p=0.41). Distribution did not differ in either direction during flood or ebb tide on neap (east-west: F=1.34, n=14 flood, n=14 ebb, p=0.25; offshore-inshore: F=1.86, n=14 flood, n=14 ebb, n=0.18) or spring (east-west: F=0, n=8 flood, n=7 ebb, p=0.98; offshore-inshore F=0.33, n=8 flood, n=7 ebb, p=0.56) tide phases.

Relative humpback whale abundance differed with tide direction (F=3.66, n=104, p=0.05) and phase (H=6.22, normal n=61, neap n=28, spring n=15, p=0.045). There were more humpback whales early in the ebb (8.83 ± 1.38 whales) than later during ebb tides (3.50 ± 0.72) (p<0.01) (Figure 6). There were more humpback whales during spring (7.53 ± 0.14 whales) than during neap (4.12 ± 0.71 whales) tide phases (p<0.05) regardless of whether the tide was ebbing or flooding.

Humpback Whale Behavior Relative to Vessels

Humpback whale swim speed differed with the number of vessels present, the distance to the nearest vessel and vessel type. Overall humpback whale swim speeds ranged from 0.02 to 28.37 km/hr and averaged 3.69 ± 0.06 km/hr. In the absence of vessels, swim speeds ranged from 0.17 to 11.85 km/hr and averaged 3.29 ± 0.20 km/hr. Swim speeds were faster (U=553254, n= 2217, p=0.02) when there were two or more vessels present (3.77 ± 0.07 km/hr) than when one or no vessels were present (3.40 ± 0.11 km/hr).

Swim speeds did not differ when there were one or more vessels vs. no vessels present (U=151726, n=2217, p=0.13). Swim speeds were faster (4.61 ± 0.50 km/hr) when the nearest vessel was within 100 m but were slower (3.70 ± 0.06 km/hr) when the nearest

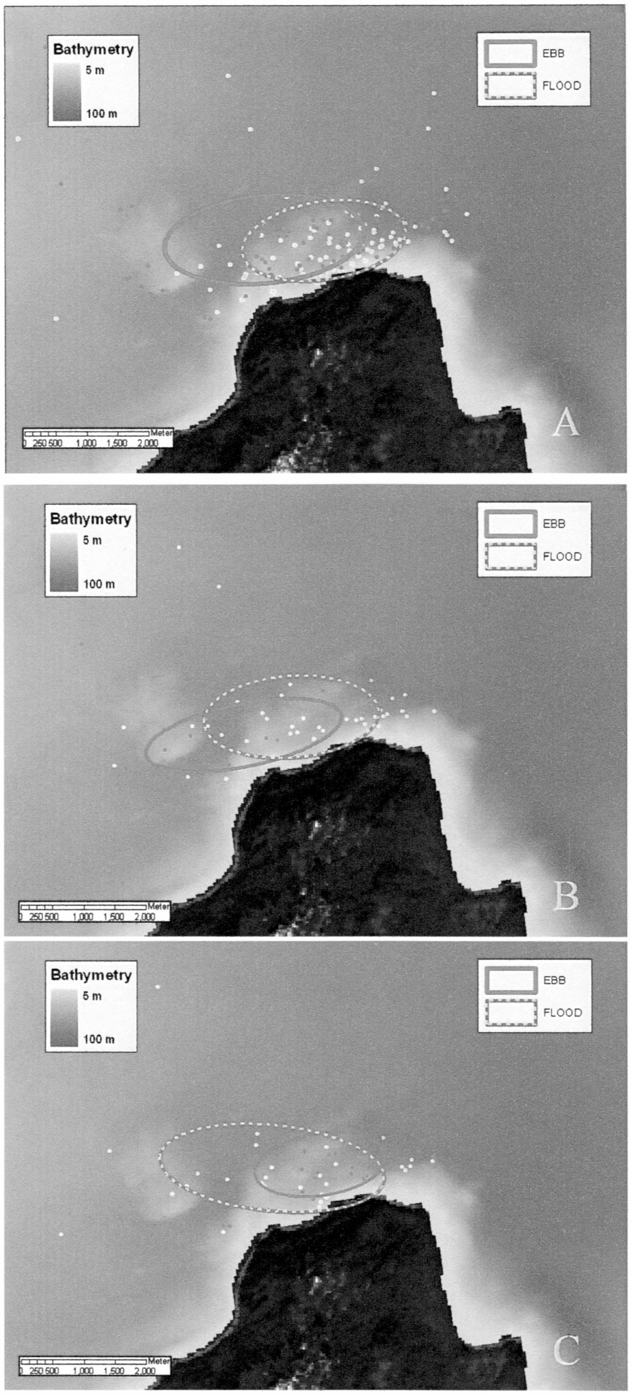

Figure 5. Humpback whale pod distribution in relation to tide. Humpback whale pod distribution observed during (A) 'normal' tides (n=61), (B) neap tides (n=28) and (C) spring tides (n=15). Yellow dots represent pods observed during flood tides and pink dots represent pods observed during ebb tides. Ellipses are one standard deviation of the x- and y-coordinates of mean center of flood and ebb distribution of pods.

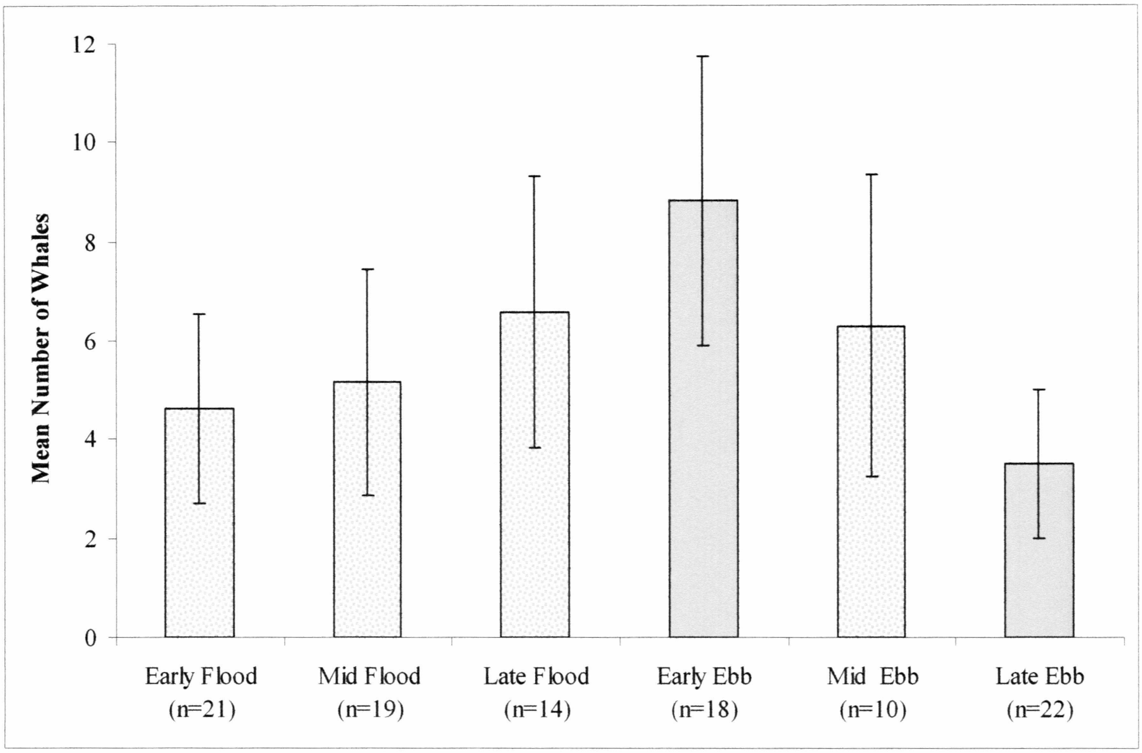

Figure 6. Humpback whale abundance in relation to tide. Means and standard errors of the number of humpback whales in relation to tide stages at Point Adolphus. Error bars are 95% confidence intervals. Solid bars differ $p<0.01$.

vessel was farther than 100 m (U=53116, n=2070, p=0.03). Humpback whales' swimming speeds averaged 3.79 $\pm$ 0.08 km/hr when the nearest vessel was within 1000 m and dropped off significantly to 3.59 $\pm$ 0.10 km/hr when the nearest vessel was farther than 1000 m (U=764821, n=2070, p=0.04). Humpback whale swim speed differed with vessel type (F=3.76, n=2070, p=0.01). However, vessel parameters in addition to the vessel-length and engine-type categories used in this study appeared to be factors in that result and were beyond the scope of this study.

Swim speeds of three of five individually-identified lone whales (referred to as known singletons) differed relative to number of vessels present and proximity of the nearest vessel. Whale #118, whale #1083 and whale #1042 each swam slower as number of vessels increased from one to two or more. Whale #118's swimming speed was 5.04 $\pm$

0.43 km/hr on average when the number of vessels was less than two and 3.48 $\pm$ 0.21 km/hr on average when there were two or more vessels present (U=2989, n=125, p=0.005). Results for whale #1083 and whale #1042 were based on small, unbalanced sample sizes (Appendix G). Swim speeds of one of five known singletons differed relative to the number of vessels present using the categories less than three vs. three or more vessels. Whale #1083 swam slower (U=2989, n=41, p=0.005) when the number of vessels was three or more (3.48 $\pm$ 0.21 km/hr) and faster when the number of vessels was less than three (5.04 $\pm$ 0.43 km/hr). Swim speeds of the other four singletons, including whale #118 and whale #1042, did not differ (Appendix G). Swim speeds of known singletons did not differ relative to distance to the nearest vessel (less than or greater than 1000 m) (Appendix G).

Whale #118, an adult male, was observed during 11 focal sessions, 12 hours total as a singleton. Whale #118's swim speeds (H=2.17, n=111, p=0.34) and dive durations (H=2.47, n=79, p=0.29) did not differ relative to distance to the nearest vessel. Whale #118's blow intervals were shorter (U=7088, n=396, p=0.01) when the nearest vessel was within 4 km (18.59 $\pm$ 0.46 sec) and longer when the distance to the nearest vessel was greater than 4 km (23.80 $\pm$ 1.70 sec).

Whale #219, an adult female, and her calf were observed during 10 focal sessions, 11 hours total as a mother and calf pod. During nine synchronous sessions, whale #219 and her calf's swimming speeds did not differ in relation to number of vessels present. However, whale #219 and her calf's swimming speeds did differ relative to distance to the nearest vessel. Whale #219 and her calf swam faster (H=11.08, n=138, p=0.004) when the nearest vessel was 500 - 1000 m (6.40 $\pm$ 0.31 km/hr) and slower when the distance to the nearest vessel was greater than 1000 m (4.00 $\pm$ 0.31 km/hr) or less than 500 m (3.90 $\pm$ 0.46 km/hr). Whale #219 and her calf's dive durations were shorter (U=648.50, n=87, p=0.02) when the distance to the nearest vessel was less than 1000 m

(205.12 $\pm$ 16.12 sec) and longer when the distance to the nearest vessel was greater than 1000 m (258.73 $\pm$ 18.69 sec).

Discussion

Humpback whales at Point Adolphus appear to have developed strategies to exploit predictable times to feed that are tidally-induced and to do so while in the presence of vessel traffic. Point Adolphus is an area with a small-scale front and headland wake effects that concentrate abundant prey resources that may influence distribution and numbers of whales. This study indicates that humpback whales at Point Adolphus change their swim speed in relation to the number, proximity and type of vessels present. Behavior change appears to be related to fine-scale vessel parameters and to vary among whales.

Oceanographic Effects

Humpback whales need high-density aggregations of prey to meet their metabolic demands (Kenney et al. 1986). Energy costs vs. energy gains are a major factor dictating the behavior of humpback whales foraging in high latitude waters (Dolphin 1988). Therefore distribution, abundance and movement patterns of humpback whales at Point Adolphus likely indicate advantageous feeding tides and locations.

Differences in humpback whale distribution, abundance and movement patterns in relation to tide direction and phase are likely related to small-scale fronts and headland wake effects at Point Adolphus. A small-scale front runs north-south from Glacier Bay to Point Adolphus; it is the boundary between shallower regions, with greater mixing to the west and deeper, more stratified regions to the east (Figure 7). Small-scale fronts are typically areas with nutrient-rich upwelling, cold water brought to the surface through mixing, and relatively higher densities of fish due to enhanced plankton production (Wolanski and Hamner 1988, Mann and Lazier 1996). During ebb and flood tides, the west-east shift in humpback whale distribution matches the movement of this front.

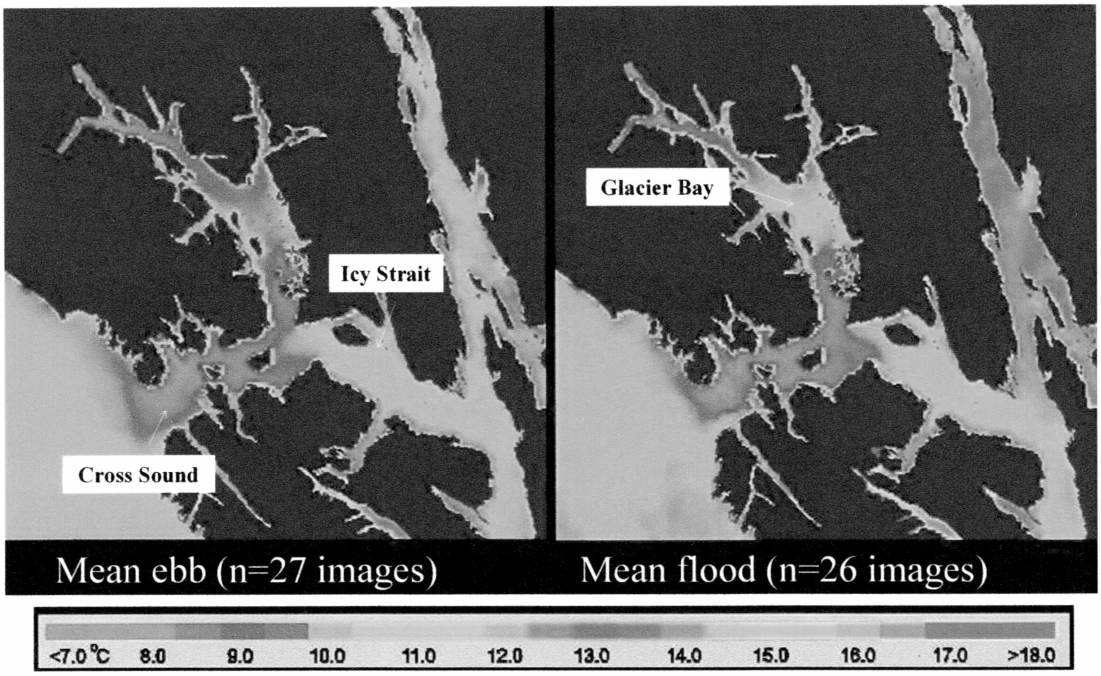

Figure 7. Sea-surface frontal region at Point Adolphus, Alaska. Mean sea-surface temperatures in Glacier Bay, Icy Strait and Cross Sound from AVHRR thermal imagery. Compilation of AVHRR images from late May-mid September 1985-2000 (n=53 images). Colder temperatures represented by purple and blue and warmer temperatures represented by turquoise (Douglas 2001).

During flood tides, the eastward shift in humpback whale distribution appears focused inside a shallow region extending from the western edge of the Point Adolphus headland. Within this region, strong current flows and differences in water depth likely form a headland wake system. Headland wake systems are made up of water masses with different current speeds and flow patterns (Johnston et al. 2005a) that create concentration mechanisms and barriers to prey. In the lee of a headland, eddies usually form (Alldredge and Hamner 1980) aggregating plankton and weak nekton into predictable locations (Wolanski and Hamner 1988). Often, a 'shear line' forms between faster and slower moving water masses aiding prey capture by acting as a barrier to small-schooling fishes (Johnston et al. 2005b).

Humpback whale abundance was greater during spring tides than during neap tides. Faster current speeds associated with spring tides may strengthen prey concentration mechanisms at Point Adolphus creating enhanced feeding conditions and attracting a greater number of humpback whales to the area. In Whitsunday Island, Queensland, Australia the density of zooplankton is up to 40 times greater in the lee of the island in direct correlation with strong tidal current velocities (Alldredge and Hamner 1980).

Humpback whale abundance at Point Adolphus was greater during early ebb than during late ebb tides. Previous studies at headlands suggest that concentration mechanisms build and prey abundance is greater during flood tide. For example in the San Juan Islands, Washington, copepods, the primary prey of juvenile herring and sandlance, are significantly more abundant during flood tides than during ebb tides (Zamon 2002). Feeding activity of mixed-species seabird flocks is greater during the early to mid flood tide than during the mid to late ebb tide and more flocks are present during the maximum flood current than during the maximum ebb current (Zamon 2003). In Bay of Fundy, density of harbor porpoise (*Phocoena phocoena*) individuals and groups is greater in the lee of the Grand Manan Island headland during the second through fifth hour of flood tide than during the second to fifth hour of ebb tide (Johnston et al. 2005a). Similarly, at Point Adolphus, numbers of humpback whales appear to increase during flood tide, as the prey concentration mechanisms build and feeding conditions become more advantageous. Whale numbers peak during the first two hours after high tide and then decrease during ebb tide, as prey concentration mechanisms weaken and feeding conditions become less advantageous.

The difference in movement patterns of humpback whales during ebb and flood tides were revealed in the availability of focal pods for study that, in turn, told us something about whale behavior. A key criterion for focal pod selection was that the pod in view remained in the area long enough to observe its behavior. Humpback whales milling (i.e., exhibiting non-directional movement) were selected for focal sessions more often while humpback whales traveling, exhibiting directional movement, were selected less often. When traveling whales were selected the session length was limited, because the whale moved out of view and the study area sooner. Non-directional movement patterns and higher turn rates, referred to as an area-restricted search pattern (Kareiva and Odell 1987), suggest foraging behavior as individuals attempt to remain near or maintain their proximity to high-density patches of prey (Stevick et al. 2002). The unintentional pattern that more focal sessions began during flood than during ebb tide suggests that was the time that pods were exhibiting an area-restricted foraging search pattern. More study is needed to determine precisely how tidally influenced oceanographic mechanisms relate to prey availability and concentration at Point Adolphus.

Vessel Effects

Humpback whale swimming speeds at Point Adolphus differed relative to the type of vessels present. Previous studies have shown that vessel underwater sound is a primary cause of whale reactions (Watkins 1986). Vessel characteristics likely responsible for changes in behavior were not addressed by this study, but may be related to differences in vessel sound production mechanisms and vessel behavior. Whales often respond to sudden or loud sounds, such as from an engine starting, a close approach, changes in direction, putting engine in and out of gear, and propeller cavitation during reverse or sharp turns (Watkins 1986).

Humpback whales exhibit different reactions and reaction thresholds in relation to vessel presence and proximity (Baker et al.1983, Bauer 1986). Humpback whales overall swam faster as the number of vessels increase from zero or one to two or more. Apparently, the presence of two vessels may cause disturbance that neither vessel would cause alone. These results match a study of bottlenose dolphins (*Tursiops sp.)* in Shark Bay, Australia in which the introduction of a second tour vessel lowered dolphins' use of the area by 15% (Bejder 2006a).

Humpback whale reactions and reaction thresholds to disturbance vary among individual whales. Three of the known singletons swam slower as the number of vessels in the area increased. Their reactions were opposite of Point Adolphus humpback whales overall and occurred at differing thresholds. Humpback whales may also have more than one reaction in relation to vessel presence and proximity (Baker et al.1983, Bauer 1986). At Point Adolphus, humpback whales overall swam faster as the distance to the nearest vessel decreased. However, whale #219 and her calf's and whale #118's reactions differed from humpback whales overall and from each other. Whale #219 and her calf exhibited a 'dual response', faster swimming speeds with shorter dive durations when the nearest vessel was within 1000 m and slower swimming speeds when the nearest vessel was within 500 m. A previous study in southeastern Alaska also illustrates a 'dual response' to vessels by humpback whales and suggests that humpbacks may use more than one strategy to avoid vessels (Baker et al. 1983). As a vessel approached within 2000-4000 m whales exhibit horizontal avoidance, i.e., swim away rapidly and vertical avoidance, i.e., dive more frequently or for a longer duration when vessels approach within 2000 m (Baker et al. 1983).

Responses and response thresholds to vessels at Point Adolphus appeared to differ among individuals, but may be related to pod composition. A study in Hawaii found that humpback whale responses and thresholds differ with pod composition (Bauer 1986). Mother-calf pods in Hawaii reacted similarly to whale #219 and her calf, in that they increased their surface time when vessel numbers increase between 500 m and 1000 m. As vessel proximity decreased, their dive durations increased. Similar to whale #118, singletons in Hawaii spend more time at the surface, slow their horizontal movement, dive repeatedly but shorten overall dive duration and increase respiration rate as vessel numbers and mean proximity to vessels decrease (Bauer 1986). However direct comparisons are difficult to interpret due to the differences in the whales' behavioral contexts in the respective study areas: i.e., humpback whales at Point Adolphus are primarily feeding while whale behaviors in Hawaii are primarily related to reproduction, calves in mother and calf pods are younger. Further study of known singletons and pods is needed to determine if responses vary among individuals or are predictable based on pod composition and size.

Humpback whales changed their behavior in relation to vessel type, numbers and proximity at Point Adolphus. However, other vessel effects may be indirect. Other factors which may affect humpback whale behavior were not included in this study, primarily distribution and abundance of prey. Changes in humpback whale swimming speed or dive depth may be responses to changes in prey movement or depth, possibly caused by vessels. For example, Atlantic herring (*Clupea harengus*) have been found to react to fishing vessels at a distance of 75-100 m by turning away from the vessel and descending (Olsen et al. 1983). Increases in humpback whale swimming speed may be in response to prey moving horizontally faster. Whale #118's decrease in swimming speed as vessel numbers increase may be an increase in dive depth or duration in response to prey moving away from the vessel. Humpback whales may need to increase their swimming speeds or change their dive behavior if prey is moving faster. Faster swimming speeds may also signify a switch from foraging to traveling. Thus, some of the whales' behavioral changes may be in response to changes in movement patterns of prey, induced by vessels, rather than a response to vessels directly.

Humpback whales at Point Adolphus are presumably changing their behavior in response to factors in their environment, i.e., prey availability, other whales, vessel activity. Behavioral changes associated directly or indirectly with vessels are considered responses to disturbance. Responses to disturbance may divert time and energy from fitness-enhancing activities (Frid and Dill 2002) such as feeding. The biological significance of anthropogenic impacts, such as vessel disturbance, is associated with long-term effects on fitness and/or distribution of whales (National Research Council 2005).

Vessel disturbance at Point Adolphus may also have a physiological impact on humpback whales. When humpback whales increase their swimming speed in relation to vessel types, number of vessels and proximity to the nearest vessel, the faster swim speed likely increases their metabolic rate. Increased metabolic rates can lower oxygen carrying capacity that can result in shorter dives (Dolphin 1987b). Short dives with high metabolic rates require relatively longer surface recovery times (Dolphin 1987b). Altering surface and dive patterns may cause humpback whales to burn more calories or may interrupt feeding, each interfering with net calorie consumption. Vessel disturbance may also interrupt feeding by displacing whales from preferred feeding areas at Point Adolphus (Baker and Herman 1989). It can be very difficult to define the level at which statistically significant differences become biologically important. However, the detection of significant average effects implies that the effects on some individuals may be severe (Richter et al. 2006). For example, significant average differences in swimming speeds of humpback whales at Point Adolphus differed by fractions of a km/hr. Differences in swimming speeds of some individuals were more extreme in relation to vessel numbers, type and proximity.

Varying responses to disturbance may suggest differences in individual tolerance (Bejder and Samuels 2003, Beale and Monaghan 2004b), possibly influenced by differences due to age or sex (Bauer 1986). Tolerant individuals may develop strategies to feed in the presence of vessel traffic while sensitive individuals may abandon the feeding area (Bejder and Samuels 2003). Individuals that remain but develop strategies to avoid disturbance are, by definition, exhibiting short-term behavioral avoidance (Bejder et al. 2006a). Individuals that switch locations are exhibiting long-term area avoidance, suggesting that the cost of remaining and tolerating disturbances exceeds the benefits of remaining in the previous location (Bejder et al. 2006a). However individuals, who display what appears to be tolerance, may have no suitable alternative habitat nearby (Gill et al. 2001). The costs of moving to alternate sites may be high for species that feed on mobile or aggregated prey, like the humpback whale, such that individuals could be forced to remain despite the disturbance (Gill et al. 2001). Behavioral changes observed at Point Adolphus suggest that the remaining whales are exhibiting short-term behavioral avoidance, but tolerating the overall disturbance. Productive habitat at Point Adolphus may compensate for vessel disturbance for at least some individuals. However, it seems likely that at least some of the less tolerant whales have left Point Adolphus because the cost of the disturbance exceeded the benefit of remaining there. For those individuals that remain at Point Adolphus despite disturbance, interruptions to feeding during the tidally-induced optimal feeding times seem likely to have a greater impact.

Many of the humpback whales in this study have been returning to Point Adolphus for decades (Neilson and Gabriele 2005). However, differing reactions and thresholds observed at Point Adolphus suggest (1) individuals may develop different strategies in response to changes in their environment, (2) some individuals may be able to tolerate disturbance that others cannot, and (3) behavioral change in the presence of vessels may be obscured when studied for the area as a whole rather than at the individual level.

Variation in response among individual humpback whales suggests that reactions to vessel activity may not be uniform across geographic areas. Areas with oceanographic features that aggregate prey, such as the features at Point Adolphus, may be extremely important to humpback whales in northern southeastern Alaska. These locations need to be identified and monitored since disturbance at these locations may have a greater impact especially during years of reduced prey abundance.

Future Study

Studies of marine mammals typically focus on short-term responses. How immediate responses are transformed into long-term changes in fitness or habitat use is unknown (Gill et al. 2001, Beale and Monaghan 2004a, Bejder et al. 2006b). Sites near Point Adolphus, in Icy Strait and particularly in Glacier Bay, have suitable qualities for longitudinal studies of humpback whale behavior in relation to vessels. Longitudinal behavior study in Glacier Bay and Icy Strait would benefit from data collected during long-term humpback whale monitoring by Glacier Bay National Park biologists.

One of the challenges of conducting a study at Point Adolphus is that the volume of vessel traffic limits opportunities for observations in the absence of vessels. An optimal study site would have similar oceanographic features and less or more controlled vessel traffic. Vessel entry into Glacier Bay is regulated. A study inside Glacier Bay National Park, at an island or headland in the lower bay, could allow observations of humpback whale behavior in the presence and absence of vessels (Appendix G). Detailed descriptions of all vessels transiting through the study area would be available through the Park permitting process. Observations of known humpback whales in the presence and absence of vessels could help account for individuality which was an important factor in the study at Point Adolphus.

The study at Point Adolphus observed behavior using focal sessions, which are useful for observations of the behavior of one pod. However during focal sessions, the activity and influence of other pods in the area are largely unknown. For example using primarily focal sessions, observations of individuals who tend to leave the study area at the approach of a vessel are difficult. This technique also introduced some bias because the tendency of individuals to remain in the observation area influenced the length of focal sessions. Future study relying more heavily on scanning would capture data missing from this study such as interactions among pods and differences in the behavior of known whales in different conditions. Future study should also include monitoring of underwater sound levels and prey distribution. Simultaneously recording underwater sound and monitoring prey distribution while observing humpback whale distribution and behavior would identify vessel sounds levels and differences in prey distribution related to humpback whale behavioral change. A hydrophone and upward looking sonar fixed to the ocean floor could be used to monitor underwater sound and prey distributions.

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